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Fast polymer integrated circuits

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Using soluble polymers for the active layer and insulating layer, we report on a concept for the fabrication of fast integrated circuits based on *p*-type organic transistors only. Ring oscillators with frequencies above 100 kHz and propagation stage delays below 0.7 μs are presented. They show a very stable performance over time even without encapsulation, when stored and measured under ambient conditions. Regioregular poly(3-alkylthiophen) is used as the active semiconducting layer, a polymer blend as the insulator, a flexible polyester film as the substrate and metal electrodes. To enable vertical interconnects, the insulating layer is patterned. [DOI: 10.1063/1.1501450]

In recent years much attention has been attracted by organic electronics. Organic field effect transistors (OFETs) are in particular a topic of intensive investigation. Several different approaches have been suggested to realize integrated circuits based on organic transistors: OFETs with semiconductors based on organic single crystals are an excellent system to investigate basic physical principles in organic materials.[1] Hybrid setups of single crystals show very good performance,[2,3] but integrated circuits have not been realized so far. Circuits based on small molecules as the semiconductor, for example, pentacene evaporated as a thin film, also show good performance, and the processing requirements are moderate.[4,5] Circuits based on polymers are easy to process due to their solubility, but until now the performance was relatively low,[6–10] even considering the lower mobility of polymers[11,12] in comparison to other organic semiconductors. Figure 1 compares the performance of these different concepts in terms of ring oscillator frequencies. The frequency as a figure of merit shows not only the maximum speed of a circuit, but also the logical capability. In the graph, only the published ring oscillator frequencies are inserted, without considering the mobility, channel length, and voltage, because the frequency is limited mainly by the circuit layout, for example, parasitic capacitances and series resistances. Circuits based on a combination of organic and inorganic semiconducting materials[13] or based on metal organic semiconductors[14] are not included in the graph, because their processing is rather complex.

From these different approaches, the general trend could be extracted that a simple setup without a complex processing technique could only result in low performance transistors and circuits. With the concept introduced in this paper, high performance polymer integrated circuits can be achieved using a simple setup that exhibits high performance, indicated by a frequency of more than three orders of magnitude faster than other results reported on polymers so far.

This concept is based on top gate OFETs with a *p*-type soluble polymer as the semiconducting layer and a soluble polymer as the insulating layer on a polymer substrate, only the electrodes are still metallic. Starting with a flexible polyester film as substrate, a 40 nm gold layer was sputtered directly on it. Using commercially available photoresist and developer, the gold drain/source electrodes are patterned with a lithography mask. The channel lengths vary from 2 to 50 μm, and the widths from 1 to 10 mm. The semiconducting polymer, *p*-type regioregular poly(3-hexylthiophene), is dissolved in chloroform and is applied by means of spin coating resulting in a 50-nm-thick layer. As an insulating layer, an organic copolymer blend with a dielectric constant of 2.5 is dissolved in dioxane and spin coated on top of the semiconducting layer. This results in a homogeneous 250-nm-thick layer without pin holes.

To enable low-ohmic vertical interconnects (vias) for integrated circuits, holes through the insulating and the semiconducting layers are realized. The insulating and semiconducting materials are removed at the positions of the vias by dissolving with an additional photolithography process. The typical hole size is $30\times30\ \mu m^2$. The transistors and the vias are completed with the deposition and patterning of the gold gate electrodes. The vias have a negligible resistance (<3 Ohm) and the yield is high (100% of 1500 vias are working). Figure 2 shows a cross-sectional view of a top gate OFET and a vertical interconnect. All processing steps are per-

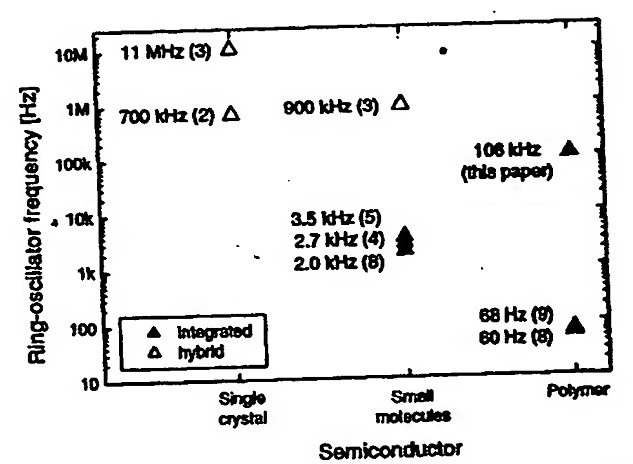

FIG. 1. Ring oscillators frequencies of different approaches for organic electronics.

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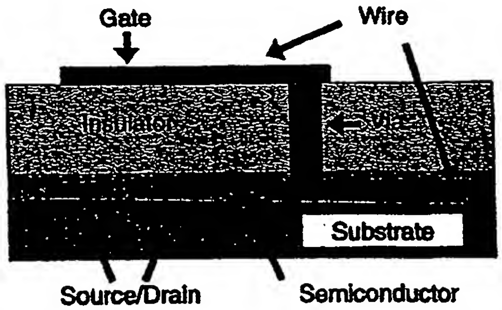

FIG. 2. Cross-sectional view of a top gate OFET and via.

formed under cleanroom conditions in the presence of oxygen and humidity. The devices were not encapsulated and were stored and measured under ambient conditions.

Electrical measurements on single OFETs show a good current saturation with a high on/off ratio. Figure 3(a) shows the output characteristics of an OFET with a channel length of $L=10\ \mu m$ and width of $W=10$ mm. From the transfer characteristics, a threshold voltage of +3 V is derived [Fig. 3(b)]. Using the standard method,[12,15] we obtained a charge carrier mobility of about 0.02 cm^2/Vs in the saturation regime [Fig. 3(b)]. The performance of integrated circuits is demonstrated by the results of a seven stage ring oscillator. Each inverter stage consists of a load OFET with $L=5\ \mu m$, $W=2$ mm and a drive OFET with $L=2\ \mu m$, $W=5$ mm. The output of the last stage is connected to the input of the first stage and to the gate of an output OFET, which has the same channel geometry as the drive OFET.

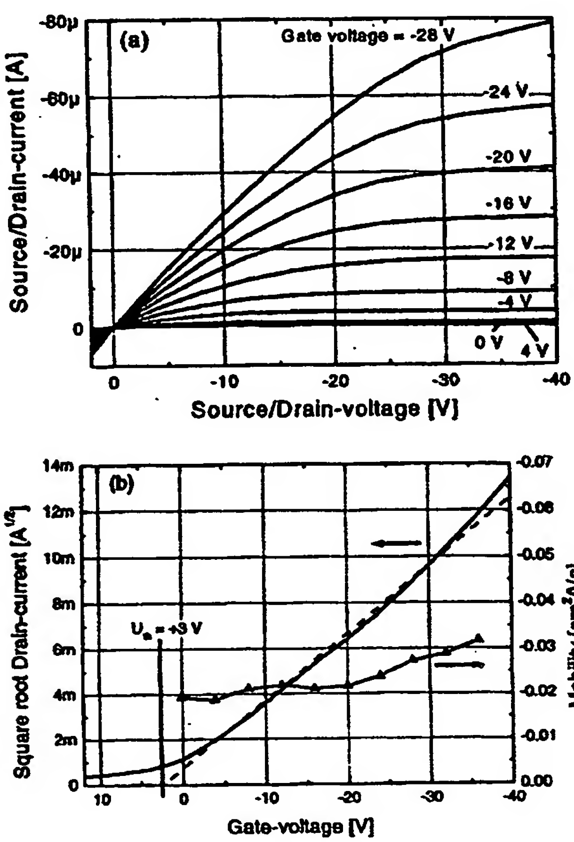

FIG. 3. Output characteristics, threshold voltage (U_{th}), and mobility.

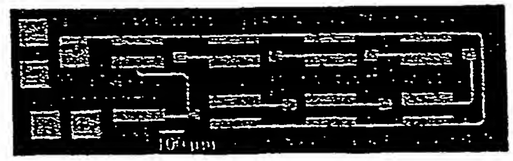

FIG. 4. Seven stage ring oscillator with output transistor.

Seven vias are necessary to connect the stages (Fig. 4). The layout of the ring oscillator allows us to apply a voltage to the gate electrodes of all load OFETs independent of the supply voltage. For typical measurements both voltages are equal. To measure the ring oscillator frequency, the channel of the output transistor is connected in series with a fast current amplifier and a common voltage of -10 V is applied. The ring oscillator starts oscillating if the supply voltage reaches an onset value, which depends on circuit design, OFET threshold voltage, and on/off ratio. With the layout mentioned above, the onset voltage was about -15 V, and with a voltage of -80 V a frequency of 106 kHz was reached (Fig. 5). This is equivalent to a stage delay of 0.68 μs.

The ring oscillator frequency is limited by the charging and discharging time of the capacitive load of a stage output, which is the sum of the input capacitance of the following stage and a parasitic capacitance. The charge and discharge currents are limited by the channel conductivity of the load OFET and drive OFET, respectively, and by series resistances, for example, contact resistance between electrodes and semiconductor. Thus, not only is the mobility crucial, but the parasitic capacitances and series resistances which result from the OFET design and the circuit layout are also of special importance.

This concept for integrated polymer circuits may be further optimized. By shifting the threshold voltage towards negative values, the supply voltage can be decreased noticeably. Other important parameters, such as mobility, parasitic capacitance, or dielectric constant of the insulator, also have the potential to be improved. Hence, even higher frequencies can be achieved. Furthermore, the processing can be simplified by using printing techniques[16] and replacing the metal electrodes with conducting polymers.[10]

Another crucial aspect is the shelf life and operation life-

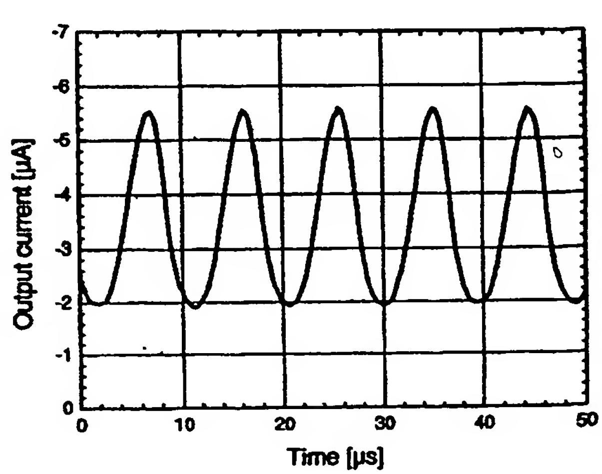

FIG. 5. Output signal of a seven stage ring oscillator.

time of the circuits. Under ambient conditions we did not detect a significant degeneration over time, even after more than 100 h of permanent oscillation of a ring oscillator. To accelerate decomposition, ring oscillators were stored in a climatic chamber with a temperature of 60 °C and 100% humidity. After 48 h under these conditions, no substantial degeneration occurred: frequency and amplitude remained nearly constant. Single OFETs, stored 14 days at 85 °C and 85% humidity, showed no substantial change in important parameters such as mobility, current saturation, on/off ratio, and threshold voltage. The performance and the stability are probably due to the encapsulation effect caused by the top gate setup used. In this construction the semiconducting layer is automatically covered by the insulator and by the gate layer.

In summary, we presented a concept for fast *p*-metal–oxide–semiconductor type integrated circuits based on soluble organic polymers. All layers involved consist of polymers, except the electrodes. High performance ring oscillators with a stage delay of 0.68 μs and a frequency of 106 kHz can be reached with this simple setup. We also demonstrated that the stability of polymer integrated circuits can be sufficiently high to be used in practical applications.

We are convinced that polymer electronics have the potential to enable applications like contactless identification tags as electronic barcodes or driving circuits for large scale organic displays. However, a requirement is that the processing of organic electronics becomes much simpler than silicon electronic processing. For that reason, inexpensive techniques such as printing processes are necessary, which are only possible with soluble materials like polymers.

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